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Direct X-ray Imaging of μm precision using Back-Illuminated CCD

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A charge-coupled device (CCD) is a standard imager in optical region in which the image quality is limited by its pixel size. CCDs also function in X-ray region but with substantial differences in performance. An optical photon generates only one electron while an X-ray photon generates many electrons at a time. We developed a method to precisely determine the X-ray point of interaction with subpixel resolution. In particular, we found that a back-illuminated CCD efficiently functions as a fine imager. We present here the validity of our method through an actual imaging experiment.

KEYWORDS: charge-coupled device, X-ray imaging, subpixel spatial resolution, mesh experiment

Charge-coupled devices (CCDs) are widely used for optical and X-ray imaging. When an X-ray photon is absorbed by photoelectric interaction in the photo-sensitive region (depletion region) of the CCD, it generates a primary charge cloud consisting of many electrons whose number is proportional to the incident X-ray energy E. The size of the primary charge cloud is $73\,(E/2.3\ \mathrm{keV})^{1.75}$nm.[1] The primary charge cloud expands through diffusion process until they reach the potential well of the CCD pixel. Therefore, the final charge cloud after the diffusion process, which is much bigger than the primary charge cloud, is accumulated into several adjacent pixels forming various types of event pattern ("grade") depending on how they split. When the entire charge is collected into one pixel (no surrounding pixels having any signal), it is called a "single pixel event" while when it splits into more than one pixel, it is called a "split pixel event".

There are two types of CCDs: front-illuminated (FI) CCD and back-illuminated (BI) CCD with basically the same structure. There are electrodes on the front side of the CCD. The depletion region is generated below electrodes while the potential well is generated very close to electrodes. Therefore, the charge is collected near the front side. The FI CCD is widely used so far in which photons enter into the depletion region from the front side. The depletion region of the FI CCD is covered by electrodes that reduce the detection efficiency for low energy X-rays and blue optical light. On the contrary, in the BI CCD, photons enter into the depletion region from the backside of the CCD. The primary charge generated near the backside of the CCD drifts toward the potential well near the front side. A BI CCD is expected to have higher detection efficiency than a FI CCD since photons enter into the depletion region without passing through the electrodes.

Tsunemi et al.[2] developed a new technique, "mesh experiment", that enables us to restrict the X-ray point of interaction with a subpixel resolution. With this technique, Hiraga et al.[3] directly measured the final charge cloud shape accumulated in the potential well through diffusion. They found that a final charge cloud shape could be well represented by a Gaussian function. They also obtained standard deviation, σ, of the final charge cloud to be $0.7 \sim 1.5\ \mu$m for $1.5 \sim 4.5$ keV by using a FI CCD. Based on this experiment, they confirmed that there are three parameters tightly coupled together:[4] the X-ray point of interaction inside the pixel, the way the final charge splits among pix-

els and the final charge cloud shape. Any two parameters can determine the third one. The event grade is quite easily measured while the final charge cloud shape is difficult to obtain. Currently, they can separately measure it only by using the mesh experiment. Therefore, they can determine the X-ray point of interaction with much better resolution than the pixel size for split pixel events. They obtained a position resolution of 0.7 μm using a CCD with pixel size of 12 μm.[5)]

Most of the X-ray photons photo-absorbed inside a FI CCD produce final charge clouds of relatively smaller size. This is due to the fact that the photo-absorption occurs near the potential well and a split pixel event occurs only when the point of interaction is near the pixel boundary. On the contrary, X-ray interaction in a BI CCD produces relatively large size of final charge cloud: $3 \sim 6$ μm and most of the X-ray photons form split pixel events.[6)] In a BI CCD, the primary charge cloud generated near the backside travels relatively longer distance before reaching the potential well, resulting the diffusion into a large size of the final charge cloud. Since the size of the final charge cloud is larger in a BI CCD and the shape can be easily obtained for most of the photons, it allows us to determine the point of interaction with much greater accuracy. We performed a demonstration that a BI CCD works as a very fine imager.

The BI CCD employed in this experiment is "S7030", manufactured by Hamamatsu Photonics Inc. It consists of 512×122 active pixels of 24 μm square. The chip is cooled down to -100°C so that we can run the CCD in a photon counting mode with low noise level. A readout noise level of 5–10 electrons is achieved by using the *E-NA* system.[7)] To use the Mo-L X-rays (2.3 keV), we employed a RIGAKU X-ray generator Ultra X-18 with a Mo target, with which we found that more than 90 % of X-ray events form split pixel events. Since the CCD is a full-frame transfer type, we used a mechanical shutter in front of the CCD so that X-rays do not enter during the readout time (2 s/frame). The X-ray intensity is also controlled such that there is no pile-up during the exposure time. Since it is relatively difficult to prepare very fine X-ray image on the CCD, we simply placed two straight metal plates forming a V-shape shadow about 2 mm above the CCD. In this way, we collected data for $\sim$6 ks during which $\sim$ 2 million of photons were accumulated. Figure 1 shows an optical image of the V-shape structure as well as the X-ray shadow.

The "V" has a sharp edge with an opening angle of 24.5°. The X-ray image in Figure 1 (b) is a sum of all the frames obtained. This is equivalent to a CCD image with a long exposure time in a photographic mode. Each pixel in the X-ray bright region contains ~100 of photons.

We run the CCD in a photon counting mode with which we confirmed that most of the X-ray photons formed split events. Among 2 million X-ray events, we selected split events such that we could improve the X-ray point of interaction. Therefore, we excluded single pixel events and two-pixel split events that constitute less than 10 % of the total events. We can measure the incident X-ray energy by adding signals from all the pixels that form the event. In this way, we selected only the Mo-L X-rays so that we could safely assume that the final charge cloud shape is a Gaussian function of $\sigma = 6\,\mu$m. The final charge cloud shape is big enough that some charge spills over the pixel forming a split event. The charge distribution among the pixels depend on the X-ray point of interaction: the closer to the pixel boundary, the more charge splits into the adjacent pixel. Then, we calculated the X-ray point of interaction for each event referring to the charge distribution among the event.

Figure 2 (a) shows an enlarged view of the region near the sharp edge in Fig 1 (b). Each small square corresponds to a CCD pixel of 24 μm square. We see that the sharp edge is rounded by the pixel size. Figure 2 (b) is the corresponding image showing the position of interaction of each individual photon determined using the final charge cloud shape and the way the charge splits among pixels. We can clearly see a sharp structure of the iamge. Judging from the X-ray wave length (~ 0.5 nm) and the distance between the V-shape structure and the CCD, the shadow is blurred by 1 μm due to the diffraction. Taking into account this effect, we believe that the position resolution is improved to less than 2 μm. However, the photon density obtained is about 100 photons/pixel that corresponds to 0.17 photons/μm^2. This is too sparse density to practically obtain a clear image with μm scale. This is an intrinsic problem in our method. The X-ray intensity should be controlled so that pile-up does not become serious in 24 μm size pixel while we need enough number of photons in 1 μm square region, which is our goal. The only method to solve this problem is to speed up readout. However, the readout speed is

limited to about 1 MHz so that we can run the system in a very low noise level in order to keep good energy resolution. At present, it is inevitable to spend long time to obtain a good spatial resolution. It may also be a problem to firmly fix the target with 1 μm scale during a relatively long exposure time.

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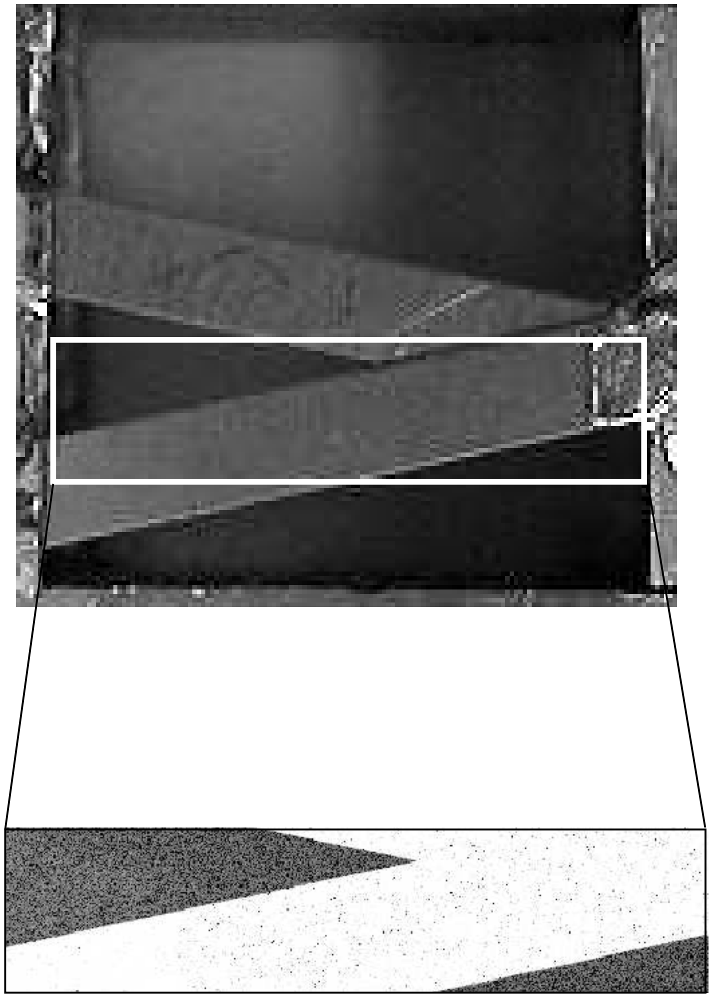
Figure captions

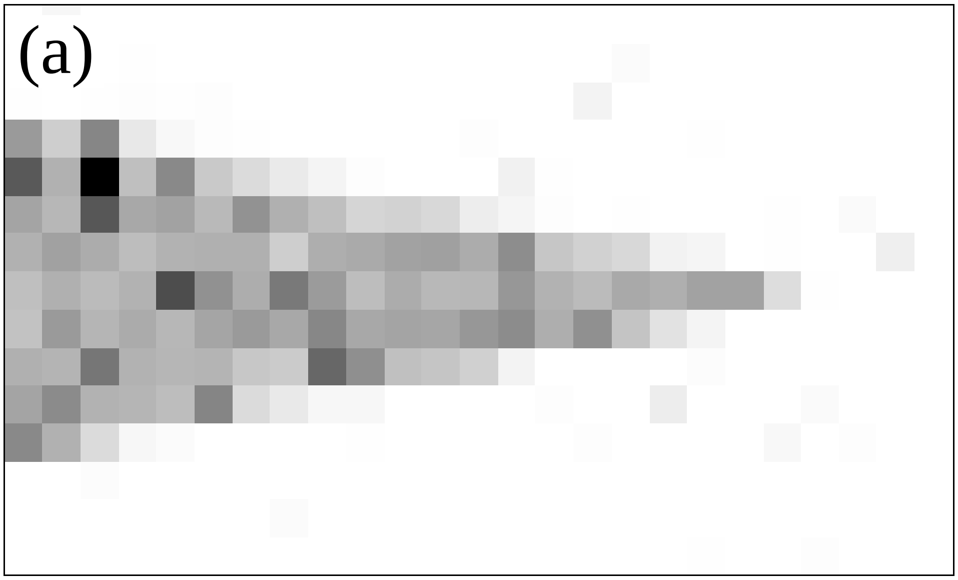
Fig. 1. (a) Optical image (12 mm square) of a V-shape structure on the CCD. (b) Enlarged image near the V-shape structure in X-ray. A sharp edge is seen.

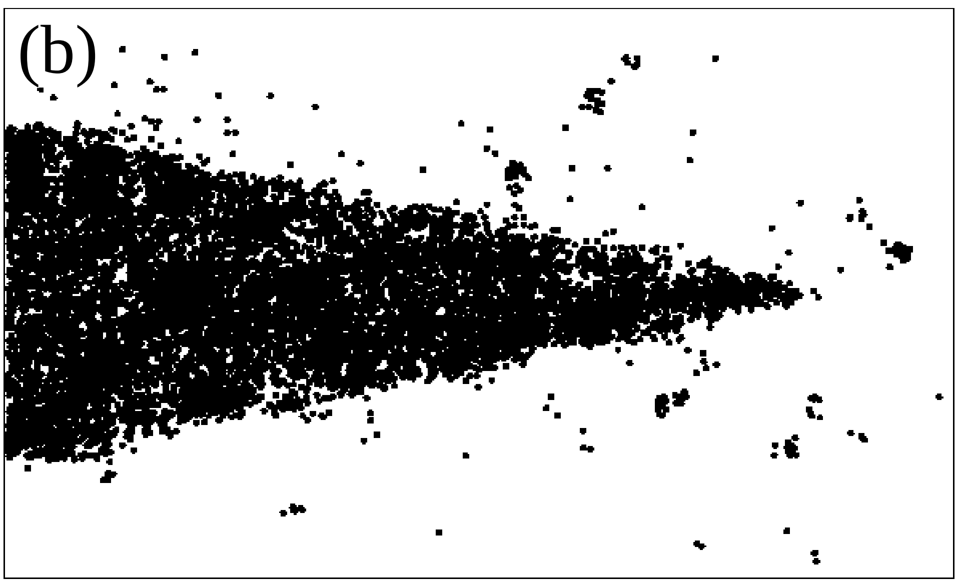
Fig. 2. (a) Simple expansion ($300 \times 500\,\mu\mathrm{m}^2$) of the X-ray image in figure 1. Squares are CCD pixels of size $24\,\mu$m. (b) Same image with improved resolution. Each dot represents an individual X-ray photon.

(a)



(b)


(a)


(b)